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# 21 Surface Pasteurization with Hot Water and Steam

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## 21.1 INTRODUCTION

The demand by consumers for fresh and fresh-cut fruits and vegetables has steadily increased due to nutritious qualities associated with fresh produce and the convenience of ready-to-eat fresh foods. This increased demand has resulted in increased per capita consumption of fresh produce. Although

Mention of trade names or commercial products in this chapter is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

fresh produce is generally considered safe, it has been implicated in numerous foodborne outbreaks in recent years. The Centers for Disease Control and Prevention reported that foodborne outbreaks associated with fresh produce doubled between the period 1973 to 1987 and 1988 to 1992 [1]. Contamination of fresh produce, often grown on the ground and/or in areas adjacent to animal production, with human pathogens may occur during growth, harvesting, handling, and processing. Conventional washing and sanitizing treatments have limited efficacy in inactivating and/or removing pathogens on the surface of produce. Survival of human pathogens and other bacteria during washing and sanitizing treatments is attributed to their attachment to inaccessible sites on produce surfaces such as within the netting of a cantaloupe [2], infiltration within the stem scar of tomatoes and the calyx region of apples [3,4], and incorporation into biofilms, as seen with apples [3], cantaloupes [2], and leaf surfaces [5,6]. Inadequate decontamination of fresh produce can result in the survival of human pathogens on the surface with the possibility of subsequent transfer of the pathogen from the surface, such as the rind of a cantaloupe or the peel of an orange, to the flesh during fresh-cut processing or juice extraction, respectively. Thus, the safety of fresh and fresh-cut produce in supermarkets and salad bars, as well as the safety of freshly squeezed unpasteurized juices, especially those served in fresh juice bars, is of concern. Although experimental approaches to washing produce, such as vacuum infiltration of sanitizers and application of abrasives during washing, have resulted in greater microbial reductions compared to conventional treatments [7], these new treatments are not capable of adequately inactivating the pathogenic bacteria in their protective attachment states on produce surfaces. Furthermore, inactivation of sanitizing agents by organic material such as soil and debris in the washing solution, prior to contact with microorganisms, may limit their sanitizing effectiveness [8].

An alternative approach to chemical sanitizers is surface pasteurization with steam or hot water. Of all the agents used to sanitize the surface of foods, water is probably the most readily acceptable to the public.

## 21.2 SURFACE PASTEURIZATION WITH HOT WATER

Unlike chemical sanitizers that only affect the surface of produce, hot water (heated potable city water) washing can inactivate bacteria below the produce surface [8], and thus is potentially more effective than chemical washes [2,8,9]. Hot water immersion provides excellent heat transfer between the produce and the heating medium [10] and can quickly establish a uniform temperature profile on the surface of produce [2,10]. Hot water surface pasteurization has been used to control insects and is the most effective method for destroying microorganisms, including postharvest plant pathogens that cause spoilage (Chapter 20). While surface pasteurization, using hot water or steam, has been shown to be effective in reducing levels of human pathogens on the surface of meat and poultry [11,12] and intact eggs [13], it has only limited use in the fresh and fresh-cut produce industries. Fresh fruits and vegetables investigated

**TABLE 21.1**
**Effect of Washing Treatment (2 minutes) on Log Reduction[a] in *Escherichia coli* O157:H7 Cell Concentration Applied to the Skin Region of Apples**

| Washing solution | Inoculated control[b] ($log_{10}$ CFU/g) | Washing temperature | |
|---|---|---|---|
| | | 25°C ($log_{10}$ CFU/g) | 60°C ($log_{10}$ CFU/g) |
| Tap water | 6.37 | 3.71 ± 0.25 AB | 4.23 ± 1.24 AB |
| 5% hydrogen peroxide | 5.24 | 3.97 ± 1.20 AB | 3.74 ± 0.68 AB |
| 1200 ppm Sanova[c] | 5.49 | 4.38 ± 0.45 AB | 4.83 ± 0.75 A |
| 400 ppm chlorine (pH[d] = 6.5) | 5.39 | 3.00 ± 1.23 ABC | 4.84 ± 0.15 A |
| Acidified electrolyzed water | 4.65 | 1.64 ± 0.19 C | 4.07 ± 0.37 AB |

[a] Log reduction = mean cell population of untreated inoculated control (duplicate samples) minus mean cell population following washing treatment (duplicate samples). Means with no letter in common are significantly different at $p < 0.05$.
[b] Mean populations of untreated inoculated control samples.
[c] Sanova (acidified sodium chlorite) solution was prepared according to the manufacturer's specifications.
[d] The pH of the chlorine solution was adjusted to 6.5 using concentrated hydrochloric acid.

for surface pasteurization include apples, melons, mangoes, lemons, oranges, cucumbers, pears, tomatoes, and alfalfa seeds.

Immersion of apples in hot water or sanitizing solutions (60°C for 2 minutes) resulted in ≥4 log CFU/g reductions in *Escherichia coli* O157:H7 populations inoculated on the skin surface (Table 21.1). However, these treatments were not effective in inactivating cells inoculated in inaccessible sites (stem and calyx) of apples (Table 21.2 and Table 21.3) [3,4]. Fleischman *et al.* [14] reported similar results for surface pasteurization of apples using water at 95°C for up to 60 seconds. Hot water immersion of apples can result in heat damage resulting in browning of the skin at temperatures above 60°C and softening of the subsurface flesh above 70 to 80°C [7,15].

Reductions in *Salmonella* Poona populations on cantaloupe surfaces were ≥5 log CFU/cm$^2$ following commercial-scale hot water immersion at 76°C for 3 minutes (Table 21.4) [2]. Also, this hot water commercial-scale treatment maintained the fresh quality and increased the shelf life of this commodity. The use of laboratory-scale hot water or heated hydrogen peroxide treatments (70 or 97°C for 1 minute) to inactivate salmonella cells on cantaloupe rind surface resulted in fresh-cut product with enhanced microbiological qualities [16] and extended shelf life [17]. Hot water immersion (70°C for 2 minutes or 80°C for 1 minute) was shown to be effective in reducing populations of *E. coli* O157:H7 on orange surfaces [18]. Also, hot water (≥57°C for 5 minutes) immersion was effective in reducing populations of *S.* Stanley on alfalfa seeds [19].

Hot water treatment of a variety of fruits and vegetables greatly improves their microbiological quality and shelf life, while maintaining their sensory qualities. Over-processing of produce, however, can significantly reduce seed germination and cause thermal injury to apples and to juice extracted from

**TABLE 21.2**
**Effect of Washing Treatments (2 minutes) on Log Reduction[a] in *Escherichia coli* O157:H7 Cell Concentration Applied to the Calyx Region of Apples**

| Washing solution | Inoculated control[b] ($log_{10}$ CFU/g) | Washing temperature | |
|---|---|---|---|
| | | 25°C ($log_{10}$ CFU/g) | 60°C ($log_{10}$ CFU/g) |
| Tap water | 6.71 | 0.19 ± 0.18 AB | 0.43 ± 0.15 AB |
| 5% hydrogen peroxide | 5.64 | 0.39 ± 0.08 AB | 0.80 ± 0.44 AB |
| 1200 ppm Sanova[c] | 5.80 | 0.48 ± 0.09 AB | 1.06 ± 0.14 A |
| 400 ppm chlorine (pH[d] = 6.5) | 6.11 | 0.66 ± 0.37 AB | 0.95 ± 0.28 A |
| Acidic electrolyzed water | 5.18 | −0.04[e] ± 0.20 B | −0.09[e] ± 0.28 B |

[a] Log reduction = mean cell population of untreated inoculated control (duplicate samples) minus mean cell population following washing treatment (duplicate samples). Means with no letter in common are significantly different at $p < 0.05$.
[b] Mean populations of untreated inoculated control samples.
[c] Sanova (acidified sodium chlorite) solution was prepared according to the manufacturer's specifications.
[d] The pH of the chlorine solution was adjusted to 6.5 using concentrated hydrochloric acid.
[e] Negative numbers indicate no reduction in cell populations was detected following washing treatment.

**TABLE 21.3**
**Effect of Washing Treatment (2 minutes) on Log Reduction[a] in *Escherichia coli* O157:H7 Cell Concentration Applied to the Stem Region of Apples**

| Washing solution | Inoculated control[b] ($log_{10}$ CFU/g) | Washing temperature | |
|---|---|---|---|
| | | 25°C ($log_{10}$ CFU/g) | 60°C ($log_{10}$ CFU/g) |
| Tap water | 6.37 | −0.10[c] ± 0.12 D | 0.11 ± 0.0.12 D |
| 5% hydrogen peroxide | 5.50 | 1.83 ± 0.17 AB | 0.96 ± 0.72 BC |
| 1200 ppm Sanova[d] | 5.66 | 2.24 ± 0.68 A | 2.04 ± 0.62 AB |
| 400 ppm chlorine (pH[e] = 6.5) | 6.53 | 0.49 ± 0.51 CD | 1.56 ± 0.26 ABC |
| Acidic electrolyzed water | 5.19 | −0.20[c] ± 0.27 D | −0.30[c] ± 0.30 D |

[a] Log reduction = mean cell population of untreated inoculated control (duplicate samples) minus mean cell population following washing treatment (duplicate samples). Means with no letter in common are significantly different at $p < 0.05$.
[b] Mean populations of untreated inoculated control samples.
[c] Negative numbers indicate no reduction in cell populations was detected following washing treatment.
[d] Sanova (acidified sodium chlorite) solution was prepared according to the manufacturer's specifications.
[e] The pH of the chlorine solution was adjusted to 6.5 using concentrated hydrochloric acid.

**TABLE 21.4**
**Efficacy of Surface Pasteurization Process Using Hot Water Immersion on *Salmonella* Poona Populations[a] on Inoculated Cantaloupes[b]**

| | Storage temperature | |
|---|---|---|
| Treatment[c] | 4°C | 20°C |
| 2 h control | 3.66 ± 0.43 | 3.66 ± 0.43 |
| 24 h control | 3.31 ± 0.16 | 5.54 ± 0.09 |
| 76°C for 3 min | 0.10 ± 0.00[d] | 0.16 ± 0.08[d] |
| Room temperature wash for 3 min | 4.23 ± 0.32 | 5.08 ± 0.20 |

[a] *S.* Poona populations were selectively isolated on XLT4 agar medium, and reported as log CFU/cm$^2$ rind.
[b] Data are reported as the mean ± standard deviation for three separate cantaloupes.
[c] Cantaloupes were dip inoculated with *S.* Poona for 5 min, allowed to air dry under biosafety cabinet for 2 h, and were stored at either room temperature or 4°C for 24 h prior to washing treatments.
[d] Although two of three cantaloupes tested showed no survivors, 0.1 log CFU/cm$^2$ (minimum detection level) was used in place of no survivors for determining the mean and standard deviation.

treated oranges. These adverse effects can be controlled by limiting treatment temperatures and times. Since individual commodities have different thermal tolerances, the hot water immersion treatment should be tailored to each commodity. While the rind of a cantaloupe [2] and the peel of an orange [18] effectively insulate the flesh from thermal damage at temperatures above 70°C, the peel of an apple does not protect the flesh from thermal damage at temperatures above 60°C [7]. Accordingly, the tolerance to hot water immersion over a range of temperatures must be determined for individual commodities at different maturity stages [15].

Following hot water immersion, produce should be rapidly cooled to reduce the risk of heat damage to the commodity [2]. This cooling process must be carefully controlled, for it is known to induce infiltration of the cooling solution, including any possible contaminating microorganisms, into the commodity [20–23]. Therefore, the cooling water to be used for this purpose should be free of human pathogens and spoilage microorganisms. A forced cold air tunnel could be used for rapid cooling of the commodity. The use of sanitizing agents during washing treatments, which includes a hot water wash, is recommended to reduce the microbial load in the washing solution. This prevents possible cross contamination in the washing tank, which could result in internalization during the subsequent cooling treatment.

## 21.3 SURFACE PASTEURIZATION WITH STEAM

Steam is a gas — gaseous water. Because water vapor molecules are many orders of magnitude smaller (about $2 \times 10^{-4}$ μm) than bacterial cells such as salmonella (4 μm long and 0.7 μm thick), and the mean free path length of water

vapor molecules (0.4 μm) is smaller than bacterial cells, steam should be able to enter any crevices or pores that bacteria can enter [24]. Steam is a unique fluid for pasteurizing food surfaces. It is sufficiently hot to kill virtually all bacterial vegetative cells on contact. However, much like hot water, treatment with steam may damage heat-sensitive foods like fruits and vegetables.

Much of the research on the use of steam for surface pasteurization has been on meat rather than fruits and vegetables. Of course, the meat-related research can be relevant to fruits and vegetables, but meats, except poultry, are generally more thermally resistant and forgiving than fruits and vegetables. Unfortunately, most of the information found on steam treatment of fruits and vegetables is not in the peer-reviewed literature but on web sites and company brochures.

In 1970 Klose and Bayne [25] experimented with steam to kill bacteria on the surface of chicken. Chicken samples were hung inside a three-necked flask, and steam was introduced under vacuum at 70 to 75°C. They obtained a 3 log reduction of naturally present bacteria with a 2-minute exposure, and a 5 log reduction after 16 minutes. Unfortunately, treatment above 60°C resulted in partial cooking of the outer layers of the samples.

In a follow-up study, Klose *et al.* [26] developed a cylindrical metal vacuum chamber to treat whole chicken carcasses with steam. Reductions of 3 logs of inoculated *S.* Typhimurium were achieved by application of subatmospheric pressure steam at 75°C for 4 minutes. However, "the cooked breast meat was almost twice as tough for steam treated as for controls (5.4 versus 3.0 kg shear) and was similarly judged by a trained taste panel," presumably because the surface was cooked.

Davidson *et al.* [27] used a double-walled steel plate steam chamber to treat whole chicken carcasses and chicken parts with 180 to 200°C steam for 20 seconds. They realized a 1 to 2 log reduction of the aerobic plate count (APC) on whole carcasses and breasts. The kill on legs and wings was 2 logs. They reported "evidence of fat separation in the skin and a lightly cooked appearance of skin and exposed muscles."

Steam has been used commercially as a surface treatment for meats [28]. Nutsch et al. [29] reported that the bacterial reduction in a commercial beef processing plant using atmospheric pressure steam for 6 or 8 seconds was 1.35 logs.

When steam is brought into contact with food surfaces, it displaces the air while compressing a very thin film of air against the food surface. This film of air insulates the food surface against direct contact by the steam. The steam is hot enough to kill bacteria instantly, but to do so it must transfer its thermal energy to the bacterial cell. With a film of air present, the steam cannot contact the bacteria directly and must transfer the energy across the compressed air film to the bacteria. This is a relatively slow process compared to condensation of steam directly onto the bacteria cell walls. The process is so slow, in fact, that the steam will cook the surface before killing the bacteria, which is detrimental to the quality of thin-skinned and heat-sensitive commodities. However, for some thick-skinned fruits and vegetables which are destined

for subsequent processing, such as for production of juice or fresh-cuts, this might not be a problem since the thermal injury would not extend into the edible portion of the commodity.

In the following sections, new steam surface pasteurization technologies applicable to fresh produce are described.

### 21.3.1 THERMOSAFE PROCESS

Thermosafe is a patented [30,31] process of Biosteam Technologies, Inc. that uses condensing steam to kill bacteria on the surface of fruits and vegetables. Steam raises the surface temperature of fruits and vegetables to a preset value for a preset hold time. Chilled water follows the steam treatment to quench cooking. Bacterial reductions of 5 logs or greater can be realized with this process. The resultant product is acceptable for produce destined for further processing. It is not acceptable for the fresh food market because the steam cosmetically degrades the surface.

#### 21.3.1.1 Process Operation

The equipment is relatively inexpensive and mechanically simple. The process consists of a chamber or steam tunnel which is designed to be integrated into a fruit or vegetable process line. The fruit or vegetable enters the chamber, usually on a conveyer, or the produce can be inserted batch mode. Pressurized saturated steam is injected through vents into the chamber to bring the surface temperature up to 74°C. Surface temperature can be monitored by contacting the surface with a thermocouple or by inserting a thermocouple into the produce 6 mm below the surface. Since this might not be reliable or practical in a continuous operation, surface temperature can also be monitored with a remote infrared sensor. After reaching 74°C, steam injection continues for a 60-second hold time. The actual time and temperature can be adjusted, but a surface temperature of 84°C degrades the organoleptic properties of fruits and vegetables. Following the hold period, chilled water at 2 to 5°C quenches the surface for another 60 seconds. The unit comes with its own steam supply and self-contained water system, including chilled water, making it easy to install and operate.

#### 21.3.1.2 Process Effectiveness

Food Safety Net Services Ltd conducted a large-scale validation study of the process [32]. The study concluded that the "process can be effective in reducing the microbial load of *Listeria monocytogenes*, *Salmonella* spp., *E. coli* O157:H7, and more thermoduric *Lactobacillus* spp. on the surface of fruits and vegetables by at least 5 logs and in some cases up to 9 logs." The data on cantaloupes show a 5 log reduction for salmonella and *E. coli*, a 7 log reduction for listeria, and a 4 log reduction for lactobacillus. For oranges the data show almost total kill, 9 logs, for salmonella, listeria, and *E. coli* and an 8 log reduction for lactobacillus. For apples, there was a 5 log reduction for

salmonella, listeria, and *E. coli* and a 7 log reduction for lactobacillus. Using a combination of steam and hot air, bacterial reductions in excess of 7 logs were realized on peppers.

#### 21.3.1.3 Product Quality

The quality of the interior portions of treated products was successfully maintained. Sensory evaluations were made on citrus juice that was extracted from fruit heated in the range of 65 to 88°C. The results of triangle tests indicated no significant differences ($p < 0.05$) in flavor between treated and untreated product. Therefore, the Thermosafe process effectively pasteurizes the surface of the tested fruits and vegetables with no significant sensory damage to the interior. These fruits and vegetables are suitable for further processing into processed products such as juice but typically would not be suitable for the fresh food market [33].

### 21.3.2 University of Bristol Process

The University of Bristol investigated the use of pressurized steam, atmospheric pressure steam, and vacuum steam for reducing the bacterial contamination of meat and fruits and vegetables [34]. The process consists of three stages: (1) noncondensable gases (air) are removed with vacuum, (2) steam is applied to the surface of the produce to reach a pasteurization temperature, and (3) the surface is evaporatively cooled under vacuum to quench cooking. Steam, with its high latent heat of condensation, gives a rapid rise in the surface temperature which minimizes thermal exposure time.

#### 21.3.2.1 Process Operation

The pressure and subatmospheric pressure process systems consist of a steam boiler, a processing chamber, and a vacuum pump. The system operates in batch mode. The pressure process chamber is 1 m by 0.6 m in diameter. The flushing action tends to remove noncondensable gases. The subatmospheric steam chamber is 0.45 m high by 0.3 m in diameter. Steam is injected in the top, and air and condensate is removed from the bottom.

With a chamber pressure of 2.3 bar, product exposure time was a nominal 90 seconds. Initial vacuum time was of the order of 10 minutes, and the evaporative cooling was about 5 minutes. Exposure times in the atmospheric pressure process were 2 to 6 seconds. Times for the subatmospheric steam process were not reported.

#### 21.3.2.2 Process Effectiveness

Although the pressure pilot plant process was applied to peppers and soft fruits, no detailed results were reported. The manufacturer reported 1.2 to 3.4 log reductions in APC of beef treated at temperatures of 100, 120, or 135°C, depending on whether it was lean or fat. In a comparison of various

decontamination methods, pressurized steam gave a 1.5 to 5 log reduction in APC on peppers. Reductions in APC for chilled raspberries and blackberries were 3 to 5 logs. The subatmospheric steam unit was used for peppers, apples, and lettuce. Bacterial reductions up to 2 logs were achieved after exposure for 10 seconds at 65°C, and up to 4 logs were achieved following exposure to 80 to 85°C for 40 seconds.

#### 21.3.2.3 Product Quality

There is no published assessment of the quality for the processed produce. Because of the temperature and time conditions of treatment, the authors suspect that the products should be suitable for further processing.

### 21.3.3 Ventilex Continuous Steam Sterilizing System

The Ventilex process uses saturated steam to decontaminate or sterilize herbs, spices, and seeds [35]. The product enters a horizontal steam chamber through a patented rotary valve, designed to prevent buildup of product within the valve. Once in the chamber, the herbs, spices, or seeds are contacted by saturated steam for a given time appropriate to reduce or eliminate pathogenic bacteria. The treated product exits through a second rotary valve. Following steam treatment, the herbs, spices, or seeds are dried and cooled.

#### 21.3.3.1 Process Operation

A description of the process is available at the Ventilex web site [35]. The process is a high-temperature/short-time treatment for herbs, spices, and seeds using saturated steam. Small particle products such as these tend to clump in valves and clog the process. This is prevented by using a continuous scraping action within the valve to dislodge any adhering product.

The treatment chamber is horizontal with a vibrating belt. The belt moves the material through the chamber in plug flow at a set speed to achieve the desired residence time. The frequency of the vibrating belt is variable and governs the flow rate that determines the dwell time for each product. Products are treated with saturated steam over the range 107 to 123°C. Typical treatment times are 25 to 50 seconds depending on the commodity, contamination level, and final use of the product. The treated product drops off the vibrating belt into a second rotary valve using the same scraping action. The herbs, spices, or seeds then go to a fluidized bed dryer/cooler. The condensed steam flashes off, and the herbs, spices, or seeds are dried with indirectly heated sterile air.

#### 21.3.3.2 Process Effectiveness

According to the manufacturer, products treated with this process often have APC counts below 1 log. Salmonella is eliminated. Mold and yeast populations

**TABLE 21.5**
**Effectiveness of the Ventilex Process on Natural Microbial Flora (log CFU/g) of Paprika and Rosemary**

| Commodity | | Aerobic plate count | Aerobic spore formers | Enterobacteriaceae | *Bacillus cereus* | Yeast | Molds |
|---|---|---|---|---|---|---|---|
| Paprika | Before treatment | 6 | 6 | 3 | 4 | 2 | 2 |
| | After treatment | 3 | 3 | — | <2 | — | — |
| Rosemary | Before treatment | 5 | 5 | 4 | — | 3 | 4 |
| | After treatment | <2 | — | — | — | — | — |

*Note:* —, not determined.
From van Gelder, A., Personal communication, 2003.

are below 2 logs. Spores of *Bacillus cereus*, *Clostridium perfringens*, and *Staphylococcus aureus* have counts below 2 log. Specific results for paprika and rosemary are shown in Table 21.5 [36]. There is a 3 log or better reduction in total APC and aerobic spore formers. Yeasts and molds are essentially eliminated.

#### 21.3.3.3 Product Quality

There is little or no product degradation. For example, the color value for paprika differed from the control by only 2 ASTA units after treatment (reduced from 95 to 93). Volatile oils for rosemary did not change (0.7 ml/100 g). In addition, the process inactivates enzymes.

### 21.3.4 Vacuum–Steam–Vacuum (VSV) Process

Thermal damage is a major problem for steam surface-pasteurized fruits and vegetables destined for the fresh market. Conventional wisdom seems to dictate that if the steam exposure time is sufficient to kill the bacteria, the produce is thermally damaged. The treated produce may be suitable for the processed fruit or vegetable market but not for the fresh market. If fresh quality is to be maintained by using a shorter exposure time, the bacterial population will not be sufficiently reduced. One solution to this problem is the U.S. Department of Agriculture's (USDA) novel VSV process [37].

To circumvent the problem of thermal damage, the film of air and moisture on the commodity surface is removed so that steam can rapidly contact the bacteria directly. It is a simple concept but difficult to achieve in practice. One approach was the concept proposed by Morgan *et al.* [24,38,39]. In this

method, the food is exposed to vacuum to remove air and moisture. Next, saturated steam is applied to the surface. When the saturated steam contacts the product, it condenses to form a water film on the fruit or vegetable surface which impedes further bacteria reduction. Therefore, the food is exposed to a vacuum again to remove the condensate and to cool evaporatively the surface. Kozempel *et al.* [40] showed that cycling between vacuum and steam to remove the condensate enhanced the population reduction of *Listeria innocua* on hot dogs. This concept of alternating vacuum and steam is the basis of the VSV process.

Initial research used a stainless steel device consisting of a rotor and stator. The 150 mm long and 150 mm in diameter [24,38] rotor was turned rapidly around its horizontal axis, stopping at precisely determined angular positions, exposing the sample alternately to vacuum or steam. A 25 mm × 75 mm × 75 mm deep treatment chamber was milled into the surface of the rotor.

The treatment consisted of four steps: (1) air was removed by exposure to vacuum; (2) the sample was flushed with low-temperature saturated steam (this flush was later abandoned); (3) the sample was exposed to pressurized saturated steam; and (4) the sample was evaporatively cooled with vacuum. Bacterial reductions on chicken meat inoculated with nonpathogenic *L. innocua* were about 2 to 2.5 logs. Steam exposure time was 0.1 to 0.2 seconds [24,38].

This prototype proved the concept, but was not practical with actual fruits and vegetables such as cantaloupes. For mechanical reasons it was preferable to move the machinery and not the food sample. Therefore, a new prototype pilot plant unit was designed and fabricated. The surface intervention processor was designed to process chicken carcasses, specifically broilers. However, the design is also suitable for many fruits and vegetables, especially cantaloupes. The performance requirements of a surface intervention processor are to accept the individual food sample and enclose it in a chamber within a rotor; to evacuate that chamber; to pressurize the chamber with steam; to vacuum cool it; and, finally, to eject the sample into a clean environment. The simplest execution of this prototype, one chamber in one rotor, was designed and constructed [41]. Figure 21.1 shows the processor, and Figure 21.2 shows details of the product treatment section. The chamber is cylindrical, about 200 mm in diameter and 240 mm deep, and is provided with an 8-inch ball valve.

To admit vacuum or steam into the closed chamber, two opposing 200 mm holes were bored through the stator at right angles to both the axis of rotation of the ball and to the centerline of the open chamber. Two platter valves, consisting of a flat disk rotating against an inlet header that holds polyetheretherketone (PEEK) seals, were close-coupled to the 200 mm ports. Each disk contained two holes, which when stopped at one of the ports in the inlet header permitted steam flow into or vacuum evacuation from the treatment chamber. Multiple holes reduced the rotor angular movement necessary for valve action and increased the cross-sectional area for gas flow. Each disk was programmed independently and moved by its own servomotor. To expose all

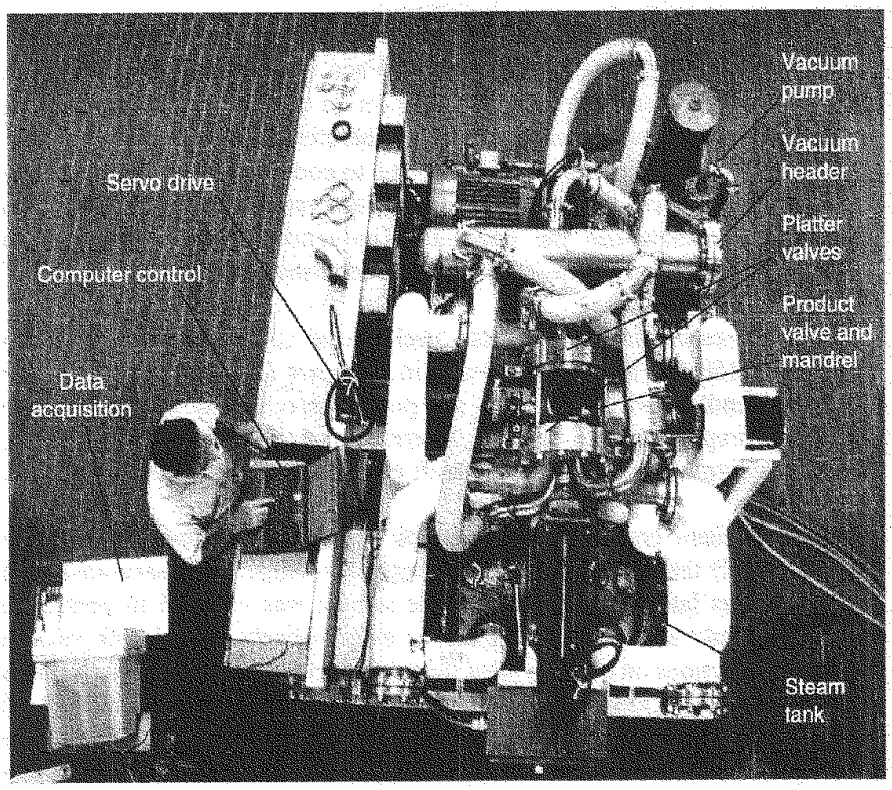


**FIGURE 21.1** Vacuum–Steam–Vacuum processor.

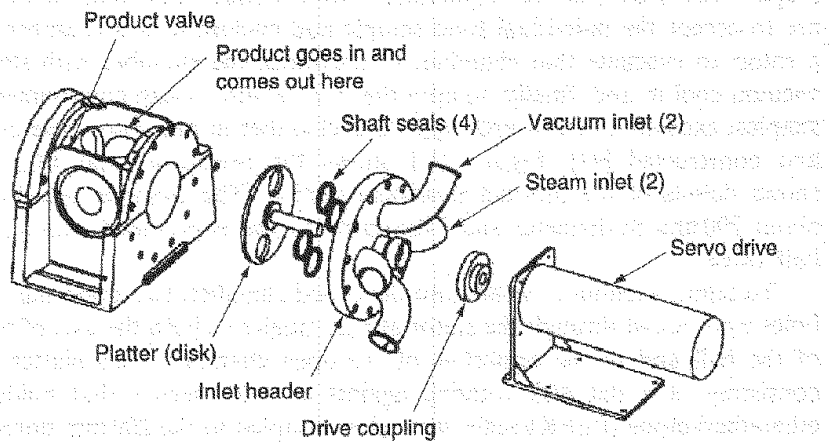


**FIGURE 21.2** Schematic of the product treatment section of the Vacuum–Steam–Vacuum processor.

exterior surfaces of the test sample to treatment, a screen was installed at the midpoint of the treatment chamber to hold the sample.

#### 21.3.4.1 Process Operation

Each sample of fruit or vegetable is manually inserted into the treatment chamber of the VSV processor. A computer-controlled servomotor is used to rotate the ball valve 90° to seal the chamber from the atmosphere. The platter valves rotate to expose alternately the sample to vacuum, then steam, and then vacuum again. With multiple cycles, the sequence of vacuum, then steam, is repeated multiple times. After treatment, the ball valve rotates back 90° to expose the sample to the atmosphere. After treatment, the fruit or vegetable sample is removed manually with sterile gloves.

#### 21.3.4.2 Process Effectiveness

Three different kinds of produce (uninoculated) were processed to assess thermal damage and bacterial reduction. The commodities were chosen to represent aerial fruits (grapefruits), fruits growing on the ground (cantaloupes), and vegetables that grow in the ground (carrots). Table 21.6 summarizes the results. There was no visual thermal damage, and the bacterial population reductions were 3.4 to >5 logs, but these process conditions were not optimized. The optimum conditions give maximum bacteria reduction with minimal or no thermal damage to the product. Therefore, a series of optimization experiments were conducted to determine the best processing conditions [41]. Beets were substituted for the in-ground crop because the shape of the treatment chamber was more amenable to spherical foods and tended to chop off the ends of carrots. (A VSV processor for carrots or other cylindrical crops would require a differently shaped treatment chamber.) Papayas were added to the list of products tested. Table 21.7 lists the optimum process condition and bacterial reduction for cantaloupes, grapefruits, papayas, and beets. Because of the high natural bacteria count on beets, they were not inoculated. Cantaloupes, grapefruits, and papayas were inoculated with *Listeria innocua*.

**TABLE 21.6**
**Initial Results for the VSV Intervention Process for Uninoculated Produce**

| Commodity | Steam temperature (°C) | Control | Population reduction |
|---|---|---|---|
| Carrots | 130 | 5.6 | >5.0 |
| Grapefruits | 130 | 3.6 | 3.6 |
| Cantaloupes | 138 | 5.6 | 3.4 |

*Note:* Vacuum time = 0.25 sec, and steam time = 0.25 sec.

**TABLE 21.7**
**Optimization Results for the VSV Surface Intervention Process on Inoculated and Uninoculated Produce**

| Commodity | Steam temp. (°C) | Steam time (sec) | Vacuum time (sec) | Number of cycles | Bacterial reduction (log CFU/ml) |
|---|---|---|---|---|---|
| Cantaloupes | 143 | 0.1 | 0.1 | 2 | 3.4 *L. innocua* |
| Grapefruits | 138 | 0.1 | 0.1 | 2 | 3.6 *L. innocua* |
| Papayas | 138 | 0.2 | 0.1 | 2 | 3.6 *L. innocua* |
| Beets | 143 | 0.2 | 0.1 | 3 | 2.5 aerobic plate count |

**TABLE 21.8**
**Application of the VSV Surface Intervention Process to Other Fruits and Vegetables**

| Commodity | Bacteria | Steam temp (°C) | Steam time per cycle (sec) | No. of cycles | Control (log CFU/ml) | Treated (log CFU/ml) | Bacterial reduction (log CFU/ml) |
|---|---|---|---|---|---|---|---|
| Mangoes | *L. innocua* | 138 | 0.1 | 2 | 5.4 | 1.4 | 4.0 |
| Avocados | *L. innocua* | 138 | 0.1 | 2 | 4.1 | 1.0 | 3.1 |
| Kiwis | *L. innocua* | 138 | 0.1 | 3 | 6.4 | 1.6 | 4.8 |
| Bananas | —[a] | 104 | 0.1 | 1 | | | Mutilated |
| Carrots | Aerobic plate count | 138 | 0.1 | 3 | 5.7 | 1.6 | 4.1 |
| Cucumbers | Aerobic plate count | 138 | 0.1 | 3 | 5.4 | 1.6 | 3.8 |
| Peaches | *L. innocua* | 138 | 0.1 | 2 | 5.0 | 1.4 | 3.6 |
| Cauliflower | —[a] | 127 | 0.1 | 1 | | | Color change |
| Broccoli | —[a] | 116 | 0.1 | 1 | | | Color change |
| Peppers | —[a] | 116 | 0.1 | 1 | | | Mutilated |

*Note:* Vacuum times = 0.1 sec.
[a] No microbiology analyses were performed on products that were thermally damaged.

Several tropical fruits were tested at the general optimum conditions of 138°C steam for 0.1 seconds using one, two, or three cycles and a vacuum time of 0.1 seconds. The results for kiwis, mangoes, and avocados are listed in Table 21.8. All samples were inoculated with *L. innocua* for 10 minutes and dried under ambient conditions for 1 hour. The log reduction for kiwis was 4.8; for mangoes, 4.0; and for avocadoes, 3.1.

Another tropical fruit, banana, was tested. However, the process caused the peel to split and the fruits to darken immediately. Milder conditions (104°C for 0.1 seconds and one cycle) were tried with green bananas, but the samples still were destroyed. No microbiological analyses were performed on products that were thermally damaged.

Other products processed without success were peppers, broccoli, and cauliflower. When subjected to vacuum, the peppers exploded. Upon exposure to steam the delicate florets on broccoli turned a bright green indicative of blanching or heat treatment. Although the flower part of cauliflower was essentially unscathed, the stalk and the remnants of the leaves turned bright green as in blanching.

Other fruits and vegetables were tested at the conditions stated above. The results are listed in Table 21.8. The bacterial reduction (APC) on uninoculated carrots was 4.1 log CFU/ml. Treatment of cucumbers, inoculated for 10 minutes with *L. innocua* and dried at ambient conditions for 1 hour, resulted in 3.8 log CFU/ml reduction with three cycles. Peaches were inoculated for 10 minutes with *L. innocua* and were allowed to dry for 1 hour under ambient conditions. Using two cycles, the reduction for *L. innocua* was 3.6 log CFU/ml with no thermal damage.

In addition to bacteria, some insects such as red scale infest the surface of fruits. Red scale is a major problem on citrus fruits. Currently, methyl bromide is used to eliminate insects such as red scale, but the impending loss of methyl bromide in 2005 requires alternative methods of quarantine treatment for disinfestations of produce imported or exported each year.

The VSV process was used to process lemons infested with red scale [42]. No scale insects survived the process. The process resulted in 100% kill of insects at all stages of development. As a bonus, up to 96% of first molt scales were physically removed, but the process was much less effective in removing other stages from the fruit, especially those that had advanced beyond the second instar. However, the process was completely effective in killing the scales.

#### 21.3.4.3 Product Quality

To date, evaluation of thermal damage has been only qualitative. Except for bananas, broccoli, and peppers that were not amenable to this process, there was no thermal damage observed. Most of the treated produce samples (uninoculated) were consumed and found to be indistinguishable from the untreated controls.

## 21.4 CONCLUSIONS

Steam and hot water surface pasteurization are both promising technologies that are capable of achieving more than 5 log reductions in target pathogens as well as greatly reducing populations of spoilage microorganisms on the surface of fruits and vegetables. However, hot water immersion treatment of fresh produce appears to be a gentler process and has better control over the surface temperature of produce during treatment as compared to steam treatment. Steam processes are acceptable treatments for produce intended for further processing due to thermal damage of the produce surface. The VSV process produces good results with a number of commodities with bacterial reductions

up to 4.8 log CFU/ml (Table 21.8), depending on the fruit or the vegetable. The VSV is a rapid process requiring less than 2 seconds for treatment and with little or no thermal damage.

Even though highly promising, surface pasteurization technology is in need of further research to determine thermal penetration profiles and heat sensitivity at different temperatures for individual commodities. There is also a need to obtain thermal inactivation data for human pathogens of concern, attached to surfaces of commodities that have subsurface sites (e.g., pores) and other sites providing protection as well as exposed sites. Furthermore, research is needed to determine the temperature–time effect of surface pasteurization on sensory qualities, storability, and processability of fresh produce at different maturity stages. Results from such research would enable the development of cheap, safe, and environmentally sound disinfection treatments for controlling pathogens and/or spoilage microorganisms on fresh produce.

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